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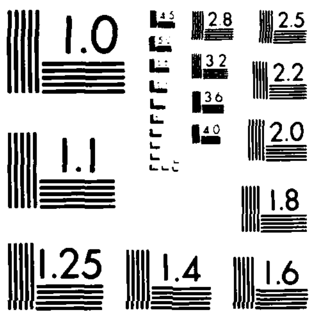

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The Response of the Total Electron Content of the Ionosphere Over North America to the Total Solar Eclipse of 26 February 1979

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4 October 1983

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SPACE PHYSICS DIVISION PROJECT 4643
AIR FORCE GEOPHYSICS LABORATORY
HANSCOM AFB, MASSACHUSETTS 01731

AIR FORCE SYSTEMS COMMAND, USAF

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**Montana State University

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Ionospheric total electron content (TEC) observations were carried out from eight stations during the total solar eclipse of 26 February 1979 over North America by monitoring changes in the Faraday rotation of the plane of polarization of vhf signals from geostationary satellites. Additionally, TEC data from ionospheric group-delay measurements were made at Vandenberg, Calif., from two 12-h synchronous NAVSTAR/Global Positioning System (GPS) satellites which crossed over the eclipsed region. Local times of totality of the eclipse in the ionosphere observed from the various stations ranged from 0730 h to

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1400 h. Depletion of the ionospheric TEC from the non-eclipse average behavior varied up to a maximum of 40 percent for the ionosphere experiencing 100 percent eclipse. Maximum TEC depletion occurred, on average, 33 min after maximum obscuration. Most of the stations showed a rapid rate of depletion of TEC about 30 min after first contact, the rate of depletion reaching a minimum value at or before maximum obscuration. Before fourth contact was reached, the rate of increase of TEC generally had overshot the non-eclipse day average, gradually returning to that average after fourth contact. Ionosonde data showed that the peak density of the F region and the TEC varied by approximately the same amount at those stations for which the E region had formed before first contact of the eclipse. Slab thickness, a first order F-region shape parameter, was not significantly changed during the eclipse.

Preface

The ionogram data and true height profiles from Boulder and Vandenberg were supplied by World Data Center A., Boulder, Colo. Special thanks go to Dr. J. Buchau for the Goose Bay ionosonde data and to Dr. H. Soicher for the Fort Monmouth ionosonde data. J. Pearson of The Aerospace Corporation kindly furnished the NAVSTAR/GPS data.

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The Response of the Total Electron Content of the Ionosphere Over North America to the Total Solar Eclipse of 26 February 1979

1. INTRODUCTION

Early research into ionospheric eclipse effects revolved around ground based techniques such as vertical incidence ionosondes and fixed frequency transmissions.[1] These techniques have now been supplemented by rocket and satellite studies as well as incoherent backscatter measurements.[2, 3] The advent of geostationary satellites in conjunction with ionosonde measurements has made possible a more detailed study of the spatial and temporal variation of eclipse effects.[4] The 26 February 1979 total solar eclipse provided an opportunity to study the response of the F region of the ionosphere over North America during a solar maximum-flux period. Previous eclipses at lower solar flux conditions produced both increases in the peak density of the F regions[5] and decreases.[3]

(Received for publication 27 September 1983)

1. Beynon, W.J.G., and Brown, G.M., Eds. (1956) Solar Eclipses and the Ionosphere, Pergamon Press, London.
2. Rishbeth, H. (1986) Solar eclipses and ionospheric theory, Space Sci. Rev. **8**:543-554.
3. Marriott, R.T., St. John, D.E., Thorne, R.M., Venkaleswaran, S.V., and Mahadevan, P. (1972) Ionospheric effects of two recent solar eclipses, J. Atmos. Terr. Phys. **34**:695-712.
4. Klobuchar, J.A., and Malik, C. (1970) Comparison of changes in total electron along three paths, Nature, **226**:1113-1114.
5. Evans, J.V. (1965) An F region eclipse, J. Geophys. Res. **70**:131-142.

2. OBSERVATIONS

Ionospheric total electron content (TEC) observations were carried out from eight stations during the 26 February 1979 total solar eclipse over North America by measuring the Faraday rotation of the plane of polarization of the vhf signals from suitably located geostationary satellites. From one of the stations, Hamilton, observations were made using four satellites. The map in Figure 1 shows the centerline of path of totality at 420 km, the location of the TEC stations together with the 420 km sub-ionospheric point along the raypath to the satellite, and the sub-satellite locations of the satellites. Titheridge[6] has shown that the use of a fixed height of 420 km yields the TEC up to 2000 km with an error of ±5 percent or less under most conditions.

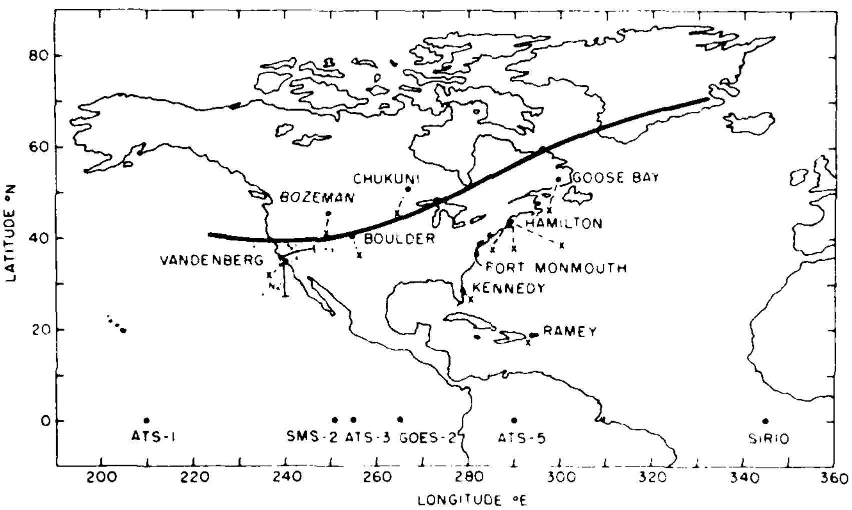

Figure 1. Map Showing the Centerline of Path of Totality at 420 km for the Total Solar Eclipse Over North America of 26 Feb 1979. The TEC stations (•) are shown together with the 420 km sub-ionospheric points (x) along the raypaths to the geostationary satellites. The nominal sub-satellite positions of the various geostationary satellite and the sub-ionospheric tracks of the two NAVSTAR/GPS satellites (N1 and N2) are also shown

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6. Titheridge, J.E. (1972) Determination of ionospheric electron content from the Faradar rotation of geostationary satellite signals, Planet. Space Sci. 20:353-369.

Table 1 lists the TEC stations, satellite beacons, and the 420 km sub-ionospheric points and their invariant latitudes. Ionosonde stations and their locations are indicated also.

Table 1. TEC Observation Sites and Ionosonde Locations

		420 km Sub-Ionospheric Point		
TEC Station	Satellite	Latitude °N	Longitude °W	Λ °N
Goose Bay	ATS—5	46.2	62.4	60
Chukini	ATS—3	45.6	95.5	58
Bozeman	SMS—2	41.3	110.5	51
Hamilton	ATS—3	38.5	75.9	53
	SMS—2	38.5	76.7	53
	SIRIO	38.1	59.8	51
	ATS—5	37.9	70.7	53
Boulder	GOES—2	36.5	104.0	47
Vandenberg	ATS—1	31.8	123.8	39
Kennedy	ATS—5	26.3	79.6	41
Ramey	ATS—5	17.1	67.4	36

Ionosonde Station	Latitude °N	Longitude °W	Λ °N
Fort Monmouth	40.2	74.1	53
Boulder	40.1	105.2	49
Vandenberg (also GPS receiving station)	34.8	120.5	40
Goose Bay	53.3	60.5	63

From Vandenberg, Calif, measurements also were made of the ionospheric group delay from two NAVSTAR/Global Positioning System (GPS) satellites in two 12-h synchronous orbits with an orbital inclination of 63 deg. The sub-ionospheric tracks of the two GPS satellites during the eclipse period are also illustrated in Figure 1.

For the two stations located in the path of totality, Chukuni and Bozeman, the time sequences of the eclipse along the raypaths from 0 to 1000 km are shown in Figures 2a and 2b. For Chukuni (Figure 2a), totality extended almost to 900 km; for Bozeman (Figure 2b), it reached almost 400 km. For both stations, the contact times occurred at earlier times with increasing height.

Ionogram data from Fort Monmouth, Boulder, Vandenberg, and Goose Bay were also used to investigate ionospheric bottomside changes during the eclipse.

3. RESULTS

3.1 Total Electron Content

Figures 3a, 3b, and 3c show the 24-h diurnal TEC results for the eight stations which monitored Faraday rotation from geostationary satellites. Figure 3a also shows the Fredericksburg K indices for 26 February 1979. A magnetic storm had occurred on 22 February and was still showing moderate activity on 26 February. Numerous small substorms were reported from 0845 UT to 1900 UT. Figures 3a, 3b, and 3c show the results for 26 February, the average for several days around the eclipse day, and the normalized average TEC curves obtained from the actual average curves by setting the two equal before first contact on the eclipse day. This procedure was adopted if the average curves differed markedly in absolute value from the curves for the eclipse day. Each plot also indicates the times of first contact, maximum obscuration, and last contact of the eclipse at a height of 300 km. The 300-km height was chosen as an average between the 420-km height centroid of Faraday rotation[6] and an assumed height of 180 km for the height of peak production.[7] The eclipse day TEC values were taken at 5-min intervals from 14 to 21 h UT; all other data were taken at 15-min intervals. For each station, the average curve was derived from available data; this varied from 2 to 6 days around the eclipse day.

The time sequences of the eclipse at 300-km height for the raypath to the geostationary satellite for each observation from each station except Ramey are shown in Figures 4a, 4b, and 4c, together with the change of the TEC, ΔN_t from the average curve, and from the normalized average curve for those stations where the actual average curve differed significantly from the TEC preceding first contact. The rate of change of TEC, dN_t/dt, is also plotted in Figures 4a, 4b, and 4c, together with that of the average curve. The time of first and fourth contacts and the maximum obscuration at 300 km are also indicated.

7. Ratcliffe, J.A., and Weekes, K. (1960) in Physics of the Upper Atmosphere, J.A. Ratcliffe, Ed., Academic Press, New York and London.

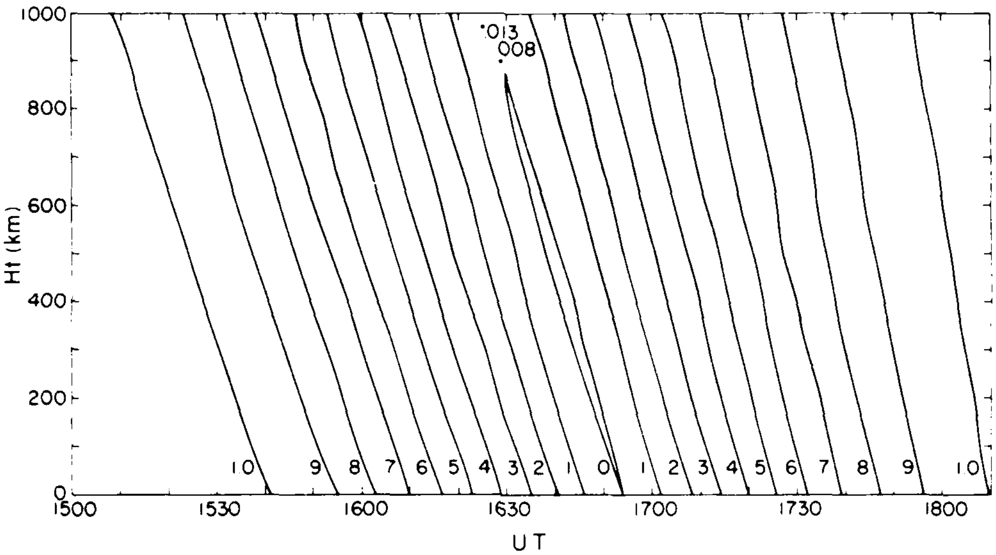

Figure 2a. Time Sequences of the Fraction of the Solar Disc Exposed During the Total Solar Eclipse of 26 Feb 1979 Along the Raypaths From 0 to 1000 km for Chukuni

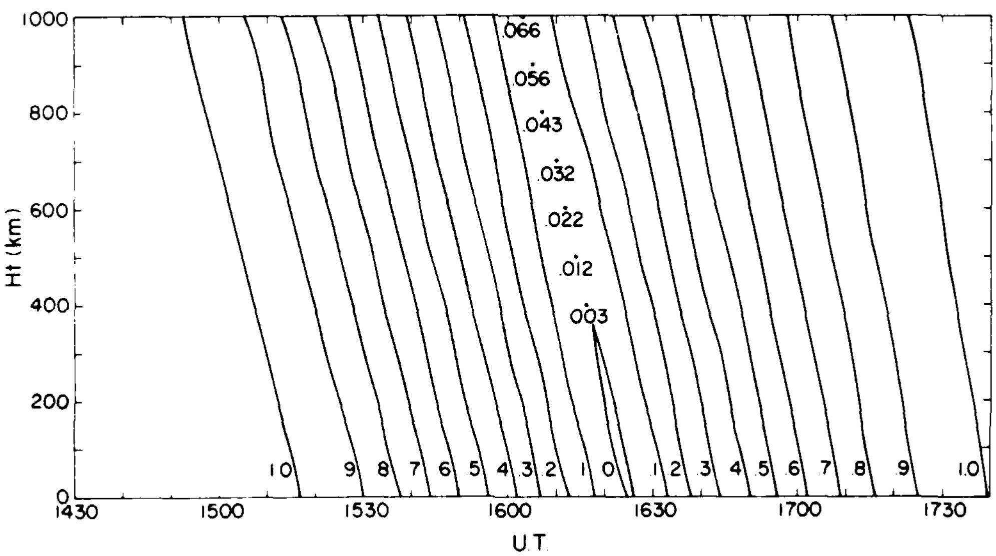

Figure 2b. Time Sequences of the Fraction of the Solar Disc Exposed During the Total Solar Eclipse of 26 Feb 1979 Along the Raypaths From 0 to 1000 km for Bozeman

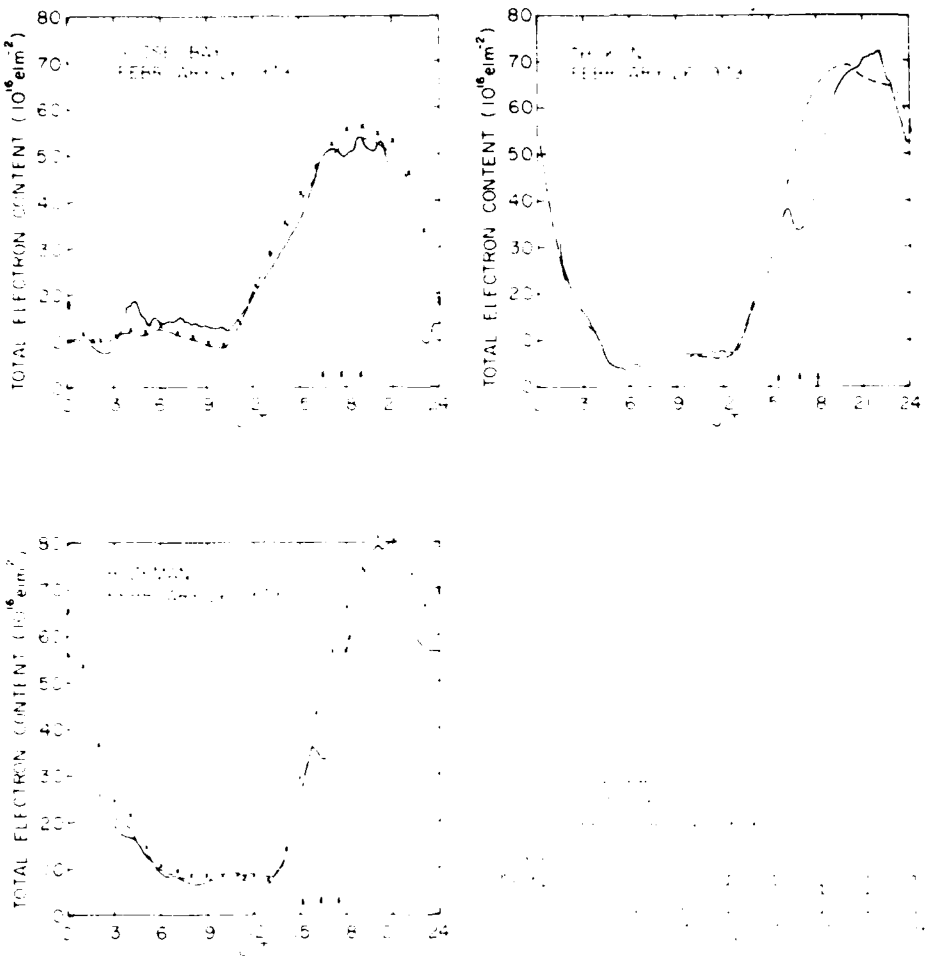

Figure 3a. 24-Hour Diurnal TEC Results for the Eclipse Day (—) Together With the Average Variation (- - -) and Normalized Average Values (x) (see Section 3, Results) From Goose Bay, Chukuni, and Bozeman. The arrows (↑) indicate the times of first contact, maximum obscuration, and last contact of the eclipse at a height of 300 km. The K indices from Fredericksburg for the eclipse day are also shown

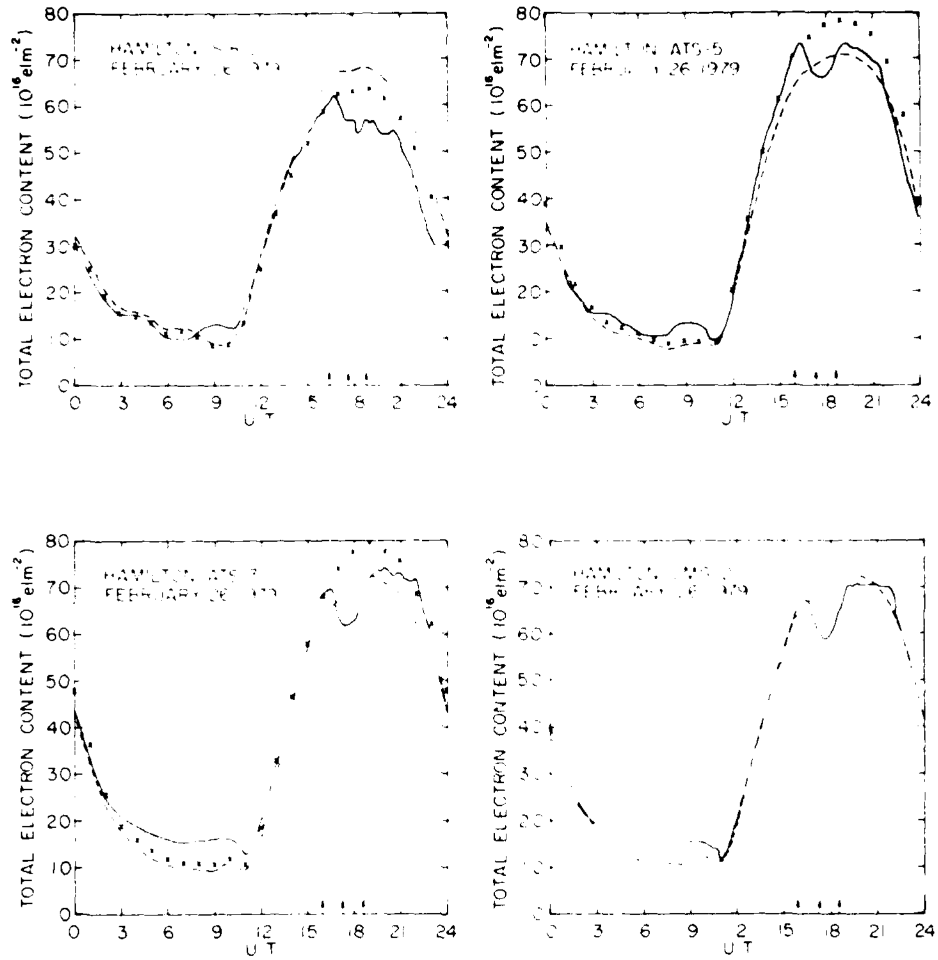

Figure 3b. 24-Hour Diurnal TEC Results for the Eclipse Day (—) Together With the Average Variation (- - -) and Normalized Average Values (x) (see Section 3, Results) From Hamilton. The arrows (↑) indicate the times of first contact, maximum obscuration, and last contact of the eclipse at a height of 300 km

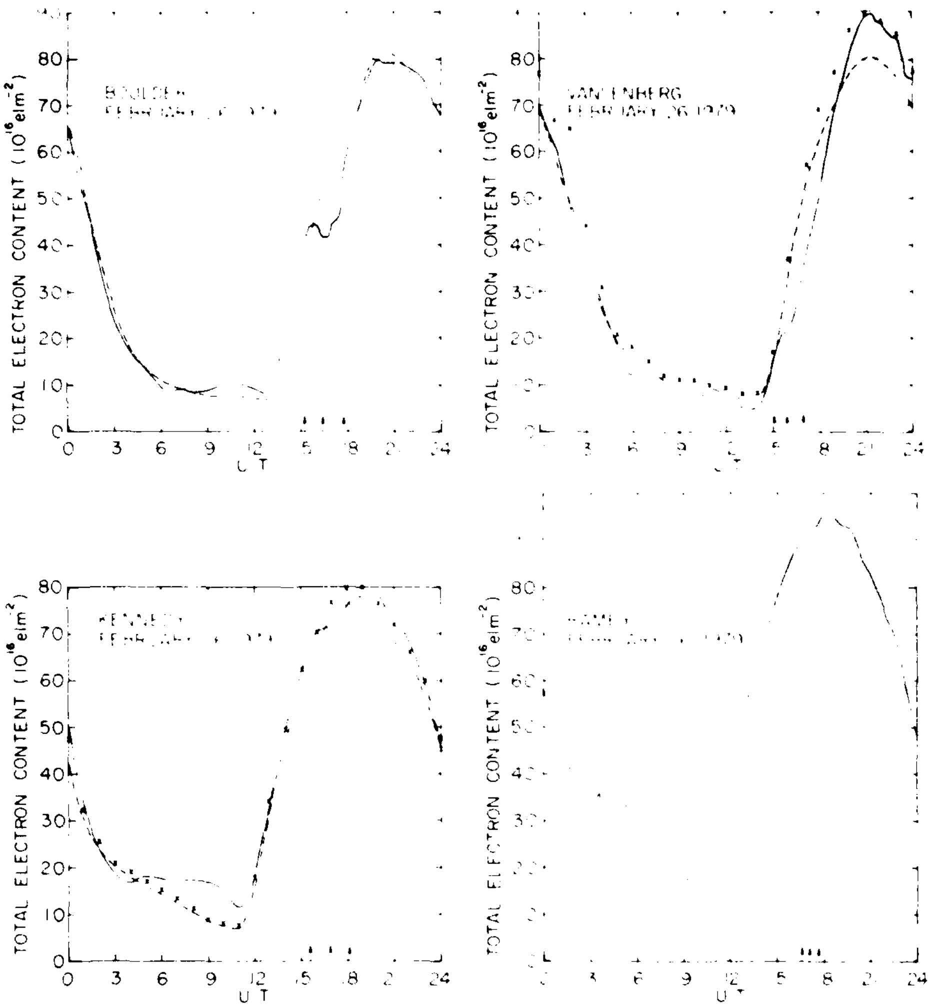

Figure 3c. 24-Hour Diurnal TEC Results for the Eclipse Day (——) Together With the Average Variation (- - -) and Normalized Average Values (x) (see Section 3, Results) From Boulder, Vandenberg, Kennedy, and Ramey. The arrows (↑) indicate the times of first contact, maximum obscuration, and last contact of the eclipse at a height of 300 km

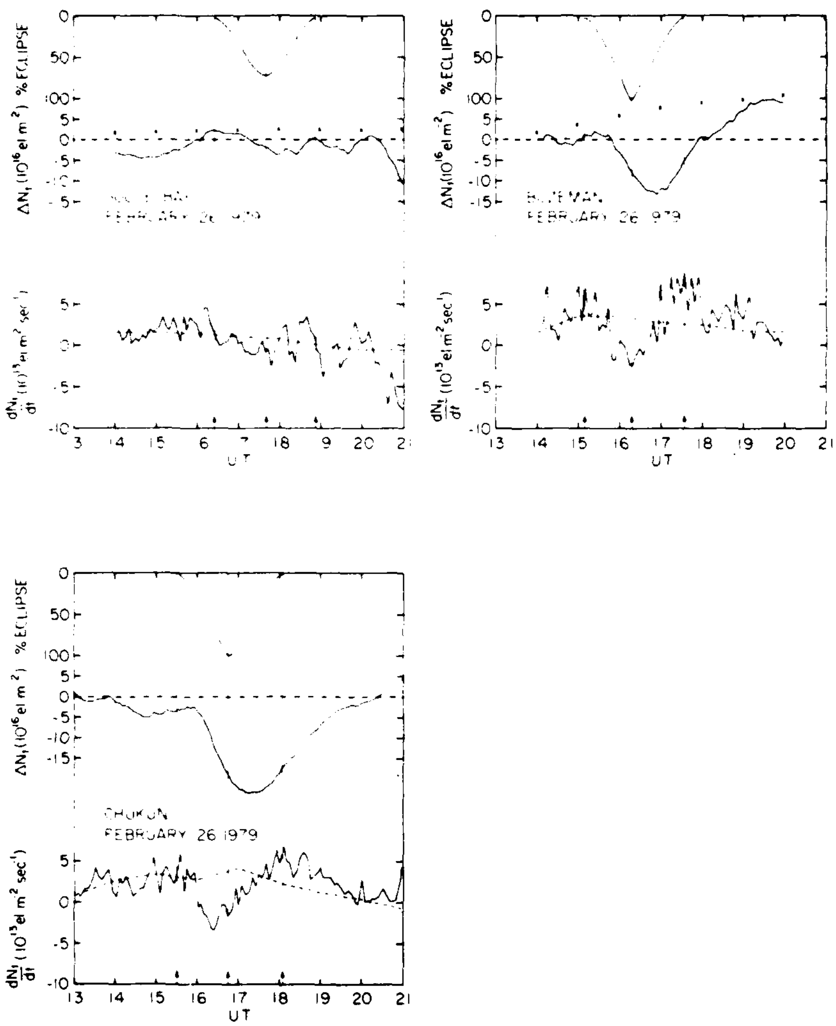

Figure 4a. Time Sequences of the Percent Solar Obscuration at 300 km, the Change in TEC, and the Rate of Change of TEC for Goose Bay, Bozeman, and Chukuni for the Eclipse Day (—), the Average Value (- - -), and Normalized Average Values (x). The vertical lines indicate the time of first and fourth contacts and the maximum obscuration at 300 km

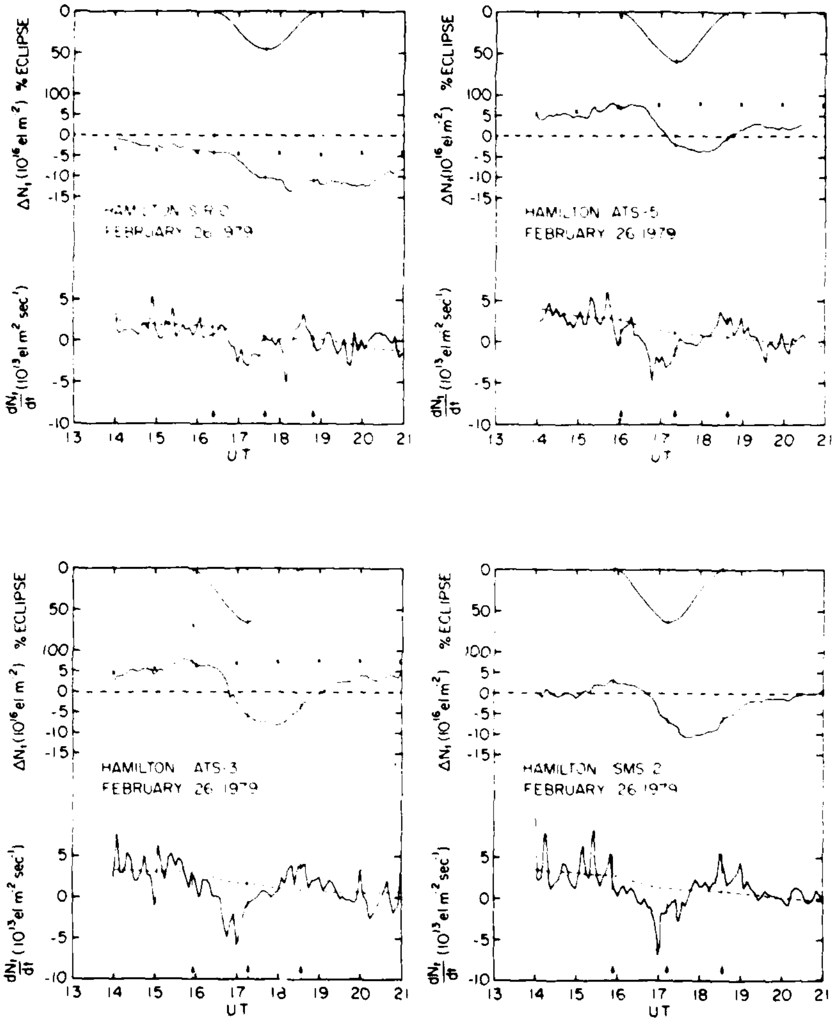

Figure 4b. Time Sequences of the Percent Solar Obscuration at 300 km, the Change in TEC, and the Rate of Change of TEC for the Four Satellites Observed From Hamilton for the Eclipse Day (—), the Average Value (- - -), and Normalized Average Values (x). The vertical lines indicate the time of first and fourth contacts and the maximum obscuration at 300 km

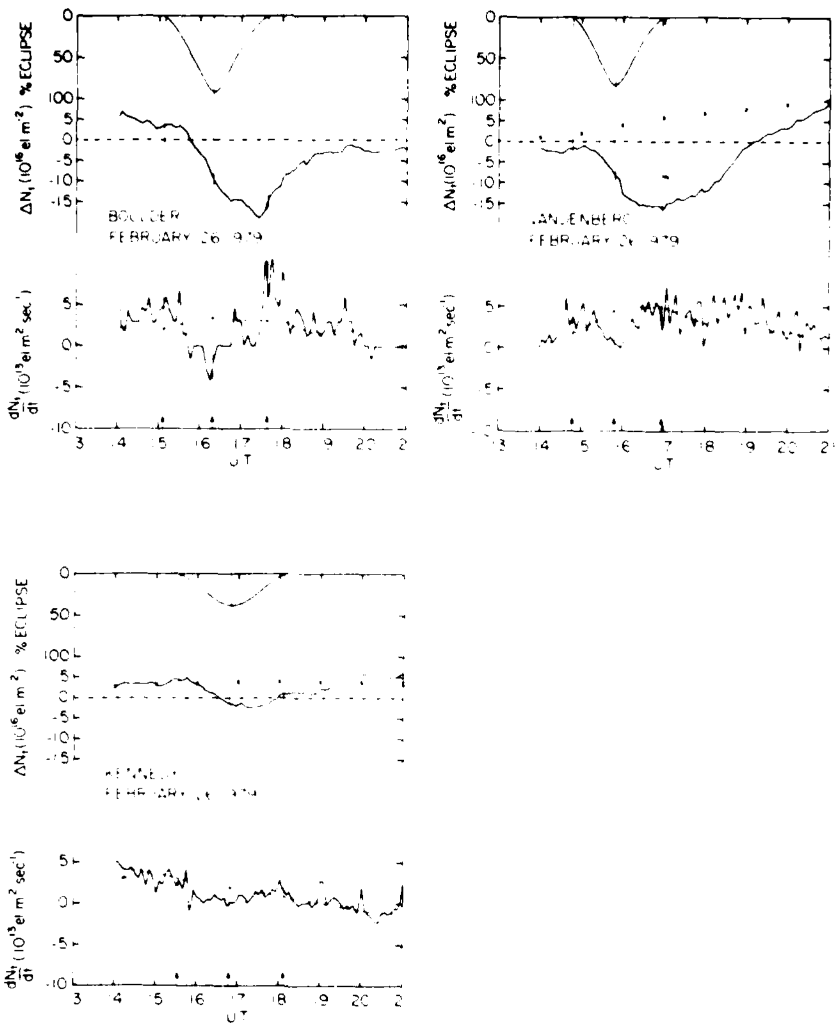

Figure 4c. Time Sequences of the Percent Solar Obscuration at 300 km, the Change in TEC, and the Rate of Change of TEC for Boulder, Vandenberg, and Kennedy for the Eclipse Day (—), the Average Value (- - -), and Normalized Average Values (x). The vertical lines indicate the time of first and fourth contacts and the maximum obscuration at 300 km

Figure 4d illustrates the change in equivalent vertical TEC from a control day as measured from the group-delay technique from two GPS satellites, along with the percent solar obscuration along the slowly changing satellite directions. The comparison day used for determining the difference due to the eclipse effects was 25 February. The group-delay method is a measure of the differential modulation

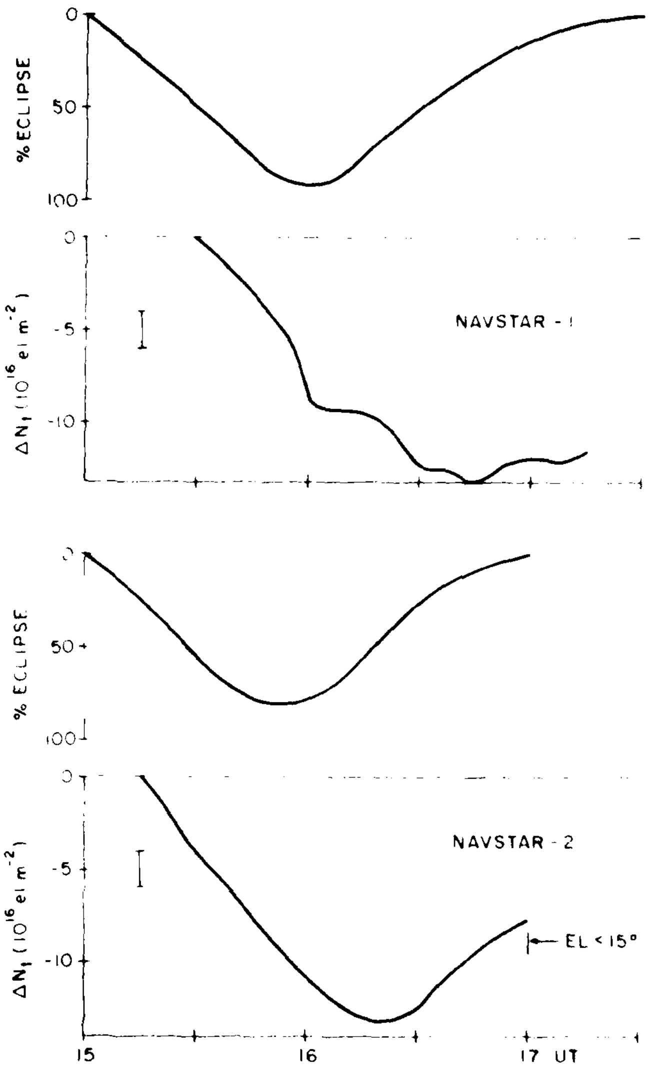

Figure 4d. Change in Equivalent Vertical TEC From a Control Day (26 Feb 1979) as Measured at Vandenberg From Two NAVSTAR/GPS Satellites

phase on two carrier frequencies transmitted from the GPS satellites and is directly proportional to the TEC along the direction to the satellite. The signals transmitted from the GPS satellites have the capability of correcting for both the time-delay effects of the earth's ionosphere and for its rate of change. In the present data, only the time delay information itself was used.

For each of the TEC eclipse day results, the time delay of minimum TEC and of maximum TEC depletion from the time of maximum eclipse were noted. Table 2 summarizes these results for each station and satellite observed, together with the eclipse contact times, percent maximum eclipse, and the TEC percent depletion.

Table 2. Time Delays of Minimum TEC and of Maximum TEC Depletion From the Time of Maximum Eclipse

Station	Satellite	300 km				TEC % Depletion	Time delay from maximum eclipse (minutes)	
		First Contact UT	Maximum UT	Fourth Contact UT	% Eclipse		Minimum TEC	Maximum TEC Depletion
Goose Bay	ATS—5	1626	1741	1854	71	11	14	14
Chukum	ATS—5	1530	1645	1804	100	40	5	30
Bozeman	SMS—2	1510	1619	1734	100	38	16	36
Hamilton	ATS—3	1554	1714	1833	64	20	11	46
	SMS—2	1554	1714	1834	67	16	31	31
	SIRIO	1625	1739	1850	47	14	36	36
	ATS—6	1604	1725	1840	59	15	35	37
Boulder	GOES—2	1506	1618	1738	92	29	12	67
Vandenberg	ATS—1	1447	1549	1653	81	9	—	11
Kennedy	ATS—5	1534	1649	1807	39	7	----	26
Ramey	ATS—5	1633	1706	1740	2	0	----	—
Vandenberg	NAVSTAR—1	1502	1607	1722	94	26	---	45
Vandenberg	NAVSTAR—2	[illegible]	1552	1658	73	30	—	27

The TEC from all of the stations except Ramey showed an effect that could be attributed to the eclipse. For the raypath from Ramey, the ionosphere was only 2 percent eclipsed at 300 km at maximum contact, and no effect that could be attributed to the eclipse was observed. While there was a decrease in TEC of approximately 11 percent observed from Goose Bay due to the eclipse, this sub-auroral station appeared to be under the influence of particle precipitation during the day of the eclipse. Further indications of particle precipitation effects are the generally irregular behavior of the TEC and the occurrence of amplitude scintillation

throughout much of the day. The magnetic activity as evidenced by K_p showed moderate activity during the eclipse period.

For the TEC results from the remaining stations, first contact commenced at local times ranging from 0632 h at the Vandenberg sub-ionospheric point to 1246 h at the Hamilton-to-SIRIO satellite sub-ionospheric point. Hence, for Vandenberg, Bozeman, Boulder, and Chukuni, the eclipse occurred during the morning increase in TEC and thus caused a delay in the morning increase. For the TEC results from Hamilton and Kennedy, the eclipse occurred near the peak of the TEC and hence caused a "bite out." However, for the Hamilton-SIRIO satellite results, fourth contact occurred at the expected daily peak time of the TEC, and hence the TEC did not recover from the eclipse depletion before the afternoon decrease commenced.[8]

For the TEC results from Chukuni, the rate of depletion showed a rapid fall after about 30 min following first contact, reaching a minimum value before maximum contact. Before fourth contact was reached, the rate of increase of TEC had overshot the non-eclipse average, gradually returning to the non-eclipse average after fourth contact. Maximum TEC depletion occurred at 30 min after maximum solar obscuration. This type of behavior was typical of most of the TEC results. Figure 5 is a graph of the percent solar obscuration of the TEC results versus the percent TEC depletion. As a first order approximation, the line of best fit for the

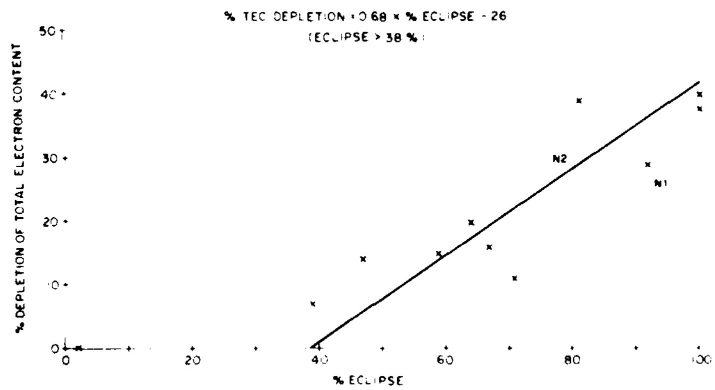

Figure 5. Graph of the Percent Solar Obscuration Versus Percent TEC Depletion Using Data From the 11 Geostationary Satellite TEC Results (x) and for the 2 NAVSTAR/GPS Satellites (N1 and N2). The line of best fit (excluding Ramey TEC data and the 2 GPS satellites) is % TEC depletion = -26 + .68 * % solar eclipse valid only for obscurations > 38 percent

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8. Morton, F.W., and Essex, E.A. (1978) Total electron content observations during 23 October 1976 solar eclipse over Southeastern Australia, J. Atmos. Terr. Phys. 40:111-114.

points is

$$\%\ TEC\ depletion = -26 + .68 * \%\ obscuration \quad (obscuration > 38\%) \tag{1}$$

Hence, for this eclipse, no measurable effect occurred in the ionospheric TEC until the obscuration of the sun exceeded 38 percent. The GPS results were omitted from the calculation of the best-fit line due to their continuously changing position.

3.2 Ionograms

Data from the Fort Monmouth, Boulder, Vandenberg, and Goose Bay ionosondes for the eclipse period were analyzed to determine the bottomside response to the eclipse. The peak density of the ionosphere was determined from the foF2 values scaled at 5-min intervals obtained from the Fort Monmouth ionosonde for the eclipse period on 26 February 1979. The results are shown in Figure 6a together with the hourly values for 24 and 25 February 1979. The Fort Monmouth peak density behavior is very similar to the Hamilton TEC results. In this case, the regions of the ionosphere being sampled are very close (see Table 1). Slab thickness (the ratio of the TEC to the peak density) was calculated using the Hamilton ATS-3 satellite. The slab thickness parameter is a first order measure of the shape of the ionospheric F-region profile. Both the eclipse day and 24 February showed increases around the same UT times. Hence, the slab thickness increases on 26 February are not necessarily the result of the eclipse.

True height reductions of the ionosonde data from Vandenberg and Boulder were carried out for the eclipse period at 15-min intervals. The bottomside TEC was obtained by integrating the true-height bottomside profile, while the topside TEC was determined by subtraction from the corresponding Faraday TEC recorded at that station. These results are plotted in Figures 6b for Boulder and Figure 6c for Vandenberg, together with the F-region peak density, height, and slab thickness. For Boulder, the peak density and slab thickness at hourly intervals on 25 February are also shown. The TEC and ionosonde data do not refer to exactly the same location, but the contact times of the eclipse are nearly co-incident. Comparison of the true height profiles (not shown), the bottomside, and topside TEC and h_mF_2 for Boulder indicates that the filling-in of the bottomside ionosphere starts after maximum obscuration, whereas the topside TEC does not start to increase for over an hour. This is partly caused by an increased in h_mF_2, although the TEC shows similar behavior. The slab thickness parameter also shows an increase of approximately 10 percent, indicating a small change in layer shape.

First contact of the eclipse at Vandenberg occurred before the E layer had

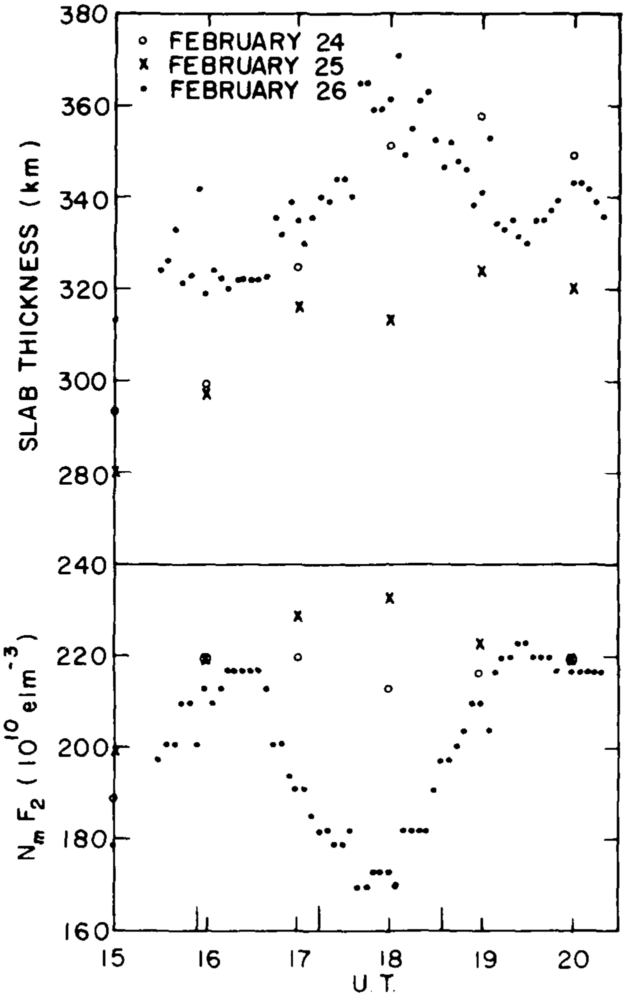

Figure 6a. Peak Density and Slab Thickness Variations at Fort Monmouth During the Total Solar Eclipse of 26 Feb 1979 at 5-Min Intervals (•), on 24 Feb 1979 at Hourly Intervals (∘), and on 25 Feb 1979 at Hourly Intervals (x)

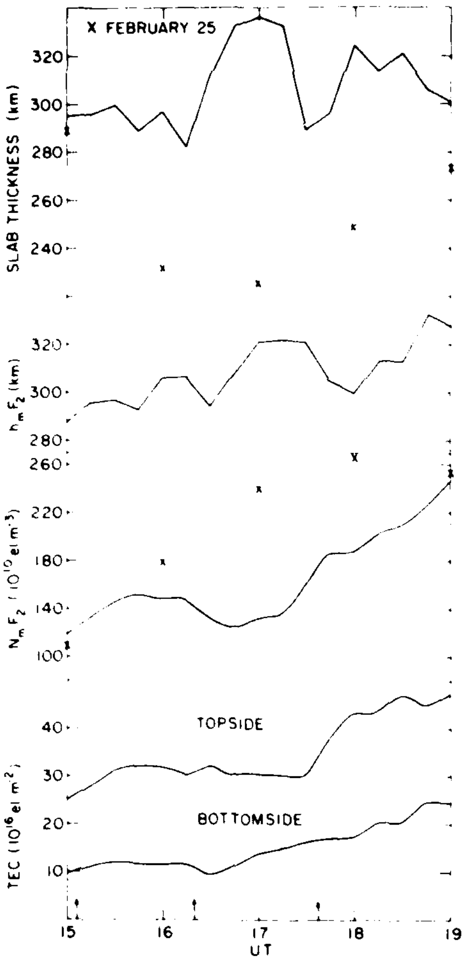

Figure 6b. Topside and Bottomside TEC, Peak Density, Peak Height, and Slab Thickness Variations at Boulder During the Total Solar Eclipse of 26 Feb 1979 (15-min values). Also shown are the peak density and slab thickness variations at hourly intervals (x) for 25 Feb 1979. The arrows (↑) indicate the eclipse contact times in the ionosphere at 300 km

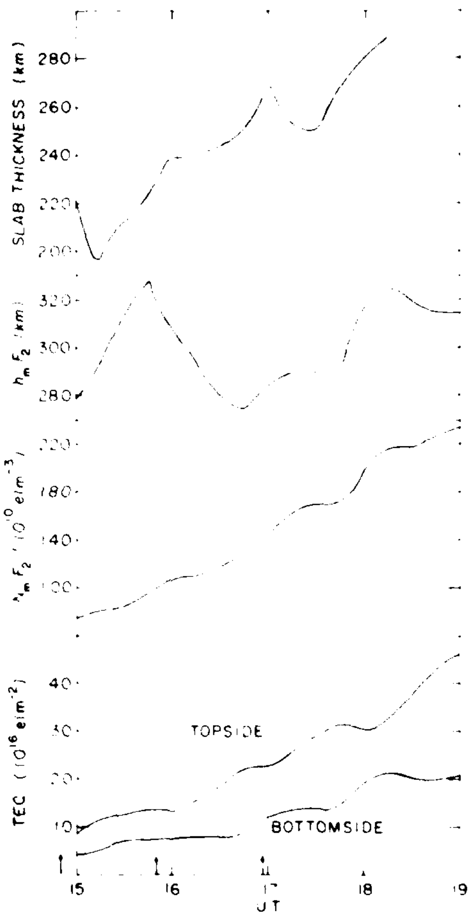

Figure 6c. Topside and Bottomside TEC, Peak Density, Peak Height, and Slab Thickness Variations at Vandenberg During the Total Solar Eclipse of 26 Feb 1979 (15-min values). The arrows (↑) indicate the eclipse contact times in the ionosphere at 300 km

formed, so bottomside observations are complicated by the normal morning formation of the E layer and its depletion by the eclipse. Large variations in the height of the peak which normally occur during the morning hours also modify the bottomside TEC results. The slab thickness parameter shows a continuous increase, indicating a change in layer shape that is also a normal daily occurrence. This is indicated on the bottomside by the changes in the true height profiles (not shown) as the E layer forms.

Figure 6d is a plot of N_mF_2 at Goose Bay on the eclipse day, 26 February, and on the two previous days, 24 and 25 February. The peak density on the eclipse

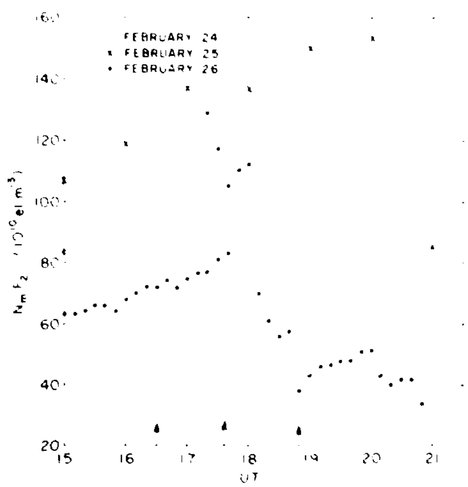

Figure 6d. Peak Density Variations at Goose Bay During the Total Solar Eclipse of 26 Feb 1979 (10-min values). Also shown are the hourly values for 24 February (∘) and for 25 February 1979 (x). The arrows (↑) indicate the first, maximum, and fourth contact of the eclipse in the ionosphere at 300 km

day was considerably less than that on the two previous days, while the TEC, shown in Figure 3a, was not significantly different. The ionosonde is located approximately 7 deg north of the 420 km height point of the TEC observations from Goose Bay. On the eclipse day, additional evidence of a large gradient in the F region was indicated by the presence of a second F2 layer of higher density. This second layer was particularly strong around 1730—1800 UT (see Figure 6d). This second layer reflection may have been caused either by auroral activity or by reflections from a higher density layer further to the south of the ionosonde as indicated by the TEC observations.

While the TEC observations did not show clear, unambiguous changes due to the eclipse, the N_mF_2 at Goose Bay showed a clear drop beginning near the time of maximum obscuration, followed by recovery near the time of fourth contact. Because of the greatly different behavior of TEC from the N_mF_2 at Goose Bay even before the start of the eclipse, likely due to the magnetically disturbed conditions on this day, no attempt was made to examine the behavior of equivalent slab thickness for these two sets of data.

4. DISCUSSION

The TEC results presented here for the total solar eclipse of 26 February 1979 across North America show that the cutoff in solar ionizing radiation produced a significant depletion in the TEC along the path of the eclipse. At one of the stations, Goose Bay, the eclipse effect in TEC was probably partly masked by particle precipitation associated with substorm events. A first order approximation shows that for this eclipse, for obscurations greater than 38 percent, a clear depletion in TEC occurred. This effect in TEC is larger than that reported by Almeida et al[9] and Marriott et al[3] for the 1970 total solar eclipse across North America. These differences may have been caused by oppositely directed vertical wind drifts during the two eclipses. For the 1979 eclipse, the path of totality was northward for all the stations except for the two stations in the path of totality, Bozeman and Chukuni.

One of the interesting features of the TEC results from most of the stations for this eclipse was the recovery of the rate of change of the TEC to values greater than the average non-eclipse values before fourth contact and their slow return to the non-eclipse values after fourth contact. Possible explanations for this effect include the modification of neutral winds and electric fields during the eclipse. This effect requires further investigation.

Investigation of the peak density and bottomside ionosphere using ionosonde data showed that the peak density and TEC depletions were similar for two of the four stations for which data were available. For the third station, Vandenberg, the eclipse commenced early in the morning before the E layer had formed; the peak density showed only small changes, although the TEC results show a large depletion. This result is probably due to the combined effect of large changes in layer height (h_mF_2) and shape (slab thickness) (see Figure 6c). Increases in slab thickness occurred at both Fort Monmouth and Boulder during the eclipse, but

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these changes cannot definitely be attributed to the eclipse because similar variations occurred on other days (see Figure 6a). Similar results have been reported by Klobuchar and Malik[4] during the 1970 total solar eclipse. For the fourth station, Goose Bay, the proximity of the auroral oval and the spatial separation of the parts of the ionosphere being sampled by the ionosonde and the Faraday rotation measurements may have led to differences in the peak density and TEC.

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